

Temperature evolution of spin accumulation detected electrically in a nondegenerated silicon channel

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(Dated: January 31, 2012)

We study temperature evolution of spin accumulation signals obtained by the three-terminal Hanle effect measurements in a nondegenerated silicon channel with a Schottky-tunnel-barrier contact. We find the clear difference in the temperature-dependent spin signals between spin-extraction and spin-injection conditions. In a spin-injection condition with a low bias current, the magnitude of spin signals can be enhanced despite the rise of temperature. For the interpretation of the temperature-dependent spin signals, it is important to consider the sensitivity of the spin detection at the Schottky-tunnel-barrier contact in addition to the spin diffusion in Si.

PACS numbers:

I. INTRODUCTION

Electrical detection of the spin accumulation is one of the important technologies to achieve semiconductor-based spintronic applications.[1] Though excellent studies of these technologies were reported for GaAs-based devices, almost all the spin-related phenomena were observed below room temperature.[2–5] In general, it has been understood that the decay of the spin signals originates from the spin-flip scattering induced by the spin-orbit interaction, hyperfine interaction between electrons and nuclei, and so on.[6] To minimize such intrinsic factors, silicon-based spintronic technologies have been proposed and developed,[7–12] and room-temperature detections of the spin-dependent signals have been reported recently.[13–15]

The temperature-dependent spin-related phenomena in Si-based devices were explored experimentally.[13, 14, 16, 17] For nondoped Si channels,[16] the relaxation of the injected spins can be explained by Yafet's $T^{-5/2}$ power law, indicating that the decay of the spin signals is attributed to the spin-flip scattering in the channel. For heavily doped Si (degenerated Si) channels, on the other hand, the decrease in the spin polarization of the injected spins is one of the main factors for the decay of spin signals.[17] However, there is no study of the temperature-dependent spin signals for nondegenerated Si channels.

In this article, we report on temperature evolution of spin signals by measuring the three-terminal Hanle effect in the lateral device with a nondegenerated silicon channel. In our device with a CoFe/Si Schottky-tunnel-barrier contact, a clear difference in the temperature-dependent spin signals between spin-extraction and spin-

injection conditions is observed. Under a certain condition, the sensitivity of the spin detection can contribute dominantly to the magnitude of spin signals detected.

II. SAMPLES AND MEASUREMENTS

The CoFe epitaxial layer was grown on Si(111) by low-temperature molecular beam epitaxy (LT-MBE) at 60 °C and the CoFe/Si interface was atomically flat.[18] A three-terminal lateral device (channel thickness ~ 100 nm, carrier density $\sim 6.0 \times 10^{17} \text{ cm}^{-3}$) with one single-crystalline $\text{Co}_{60}\text{Fe}_{40}$ contact and two AuSb ohmic ones with lateral dimensions of $10 \times 200 \mu\text{m}^2$ and $100 \times 200 \mu\text{m}^2$, respectively, was fabricated by using conventional processes with photolithography, Ar^+ ion milling, and reactive ion etching.[11, 15, 19] The schematic diagram of the device structure is shown in the inset of Fig. 1(e). The distance between CoFe and AuSb is about $\sim 50 \mu\text{m}$. To achieve tunneling conduction through the high-quality CoFe/Si interface, we inserted Sb δ -doped n^+ -Si layer ($\text{Sb} \sim 5 \times 10^{19} \text{ cm}^{-3}$) with a thickness of 5 nm between the epitaxial CoFe layer and n -Si channel.[11, 15, 19] As a result, we obtained tunneling conduction having nonlinear $I - V$ characteristics through the interface and the rectification is quite small, as shown in Fig. 1(a). Therefore, we can regard the fabricated $\text{CoFe}/n^+\text{-Si}/n\text{-Si}$ contact for spin injection and extraction as a Schottky-tunnel-barrier contact. Hanle-effect measurements with a three-terminal geometry were performed by a dc method at 40 \sim 300 K. In the measurements, a small magnetic field perpendicular to the plane, B_z , was applied after the magnetic moment of the CoFe contact aligned parallel to the plane along the long axis of the contact.

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III. RESULTS AND DISCUSSION

Spin accumulation in semiconductor channels can be detected electrically by measuring three-terminal voltage changes (ΔV_{3T}) via Hanle-type spin precessions.[2, 13, 15, 19] Figures 1(c) and 1(d) show representative ΔV_{3T} - B_Z curves for $I = -1.0$ and $1.0 \mu\text{A}$ at 40 K. The electrons are injected into and extracted from, respectively, the Si conduction band for reverse ($I < 0$) and forward ($I > 0$) biases, where quadratic background voltages depending on B_Z are subtracted from the raw data. We note that clear Hanle-effect signals were observed for both bias-current conditions but the sign of the voltage change is opposite. Such sign reversal was seen only when the polarity of I was switched. These curves were fitted with a simple Lorentzian function,[13] $\Delta V_{3T}(B_Z) = \Delta V_{3T}(0)/[1+(\omega_L\tau_S)^2]$, where $\omega_L = g\mu_B B_Z/\hbar$ is the Larmor frequency, g is the electron g -factor ($g = 2$), μ_B is the Bohr magneton, τ_S is the lower limit of spin relaxation time. The fitting results are denoted by the red solid curves. The τ_S values for $I = -1.0$ and $1.0 \mu\text{A}$ are estimated to be ~ 4.37 and ~ 2.05 nsec, respectively. The precise origin of the difference in τ_S between $I = -1.0$ and $1.0 \mu\text{A}$ is unclear yet, but we can consider a possible difference in the relative position of the spin accumulation in n -Si to the n^+ -Si layer, as illustrated in Fig. 1(b). There may be some differences in the influence of the n^+ -Si layer on spin relaxation between spin injection ($I < 0$) and extraction ($I > 0$) conditions.

We hereafter focus on the magnitude of ΔV_{3T} , $|\Delta V_{\text{Hanle}}|$, for various temperatures. Figure 1(e) displays $|\Delta V_{\text{Hanle}}|$ versus bias current I ($-2.0 \mu\text{A} \leq I \leq 2.0 \mu\text{A}$) at 40, 50, 75, and 100 K. We can see clear asymmetric variation in $|\Delta V_{\text{Hanle}}|$ with respect to the polarity of I . [20] For $I > 0$, $|\Delta V_{\text{Hanle}}|$ decreases with increasing temperature in all I region while, for $I < 0$, complicated variations in $|\Delta V_{\text{Hanle}}|$ are seen, particularly, in $-1.0 \mu\text{A} \leq I \leq 0 \mu\text{A}$. We can see that $|\Delta V_{\text{Hanle}}|$ at 100 K is larger than that at 50 K. Concentrating on this interesting phenomenon, we further explored temperature-dependent $|\Delta V_{\text{Hanle}}|$ for various I in detail. Figures 2(a) and 2(b) show $|\Delta V_{\text{Hanle}}|$ as a function of temperature for spin-extraction ($I > 0$) and spin-injection ($I < 0$) conditions, respectively. The features observed are summarized as follows: (i) Temperature evolution of $|\Delta V_{\text{Hanle}}|$ shows a clear difference between spin-extraction ($I > 0$) and spin-injection ($I < 0$) conditions. (ii) $|\Delta V_{\text{Hanle}}|$ can be detected even at room-temperature with a large injection current of $-20 \mu\text{A}$ in $I < 0$ [see the inset of Fig. 2(b)], whereas $|\Delta V_{\text{Hanle}}|$ is markedly reduced with increasing temperature and disappears at 250 K irrespective of I in $I > 0$. τ_S for $I = -20 \mu\text{A}$ at room temperature can be estimated to be 1.36 nsec. The τ_S value decreases with increasing temperature from 3.02 to 1.36 nsec, consistent with the feature observed in the heavily doped Si.[14, 17] (iii) In $I = -0.1$ and $-1.0 \mu\text{A}$ we can see the partial increases in $|\Delta V_{\text{Hanle}}|$ despite the rise of temperature [see arrows in Fig. 2(b)].

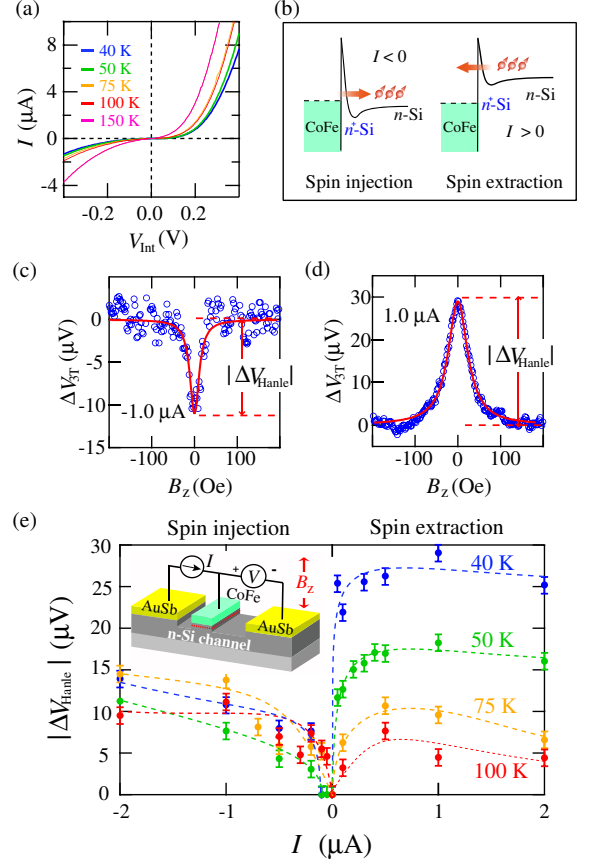


FIG. 1: (Color online) (a) $I - V_{\text{Int}}$ characteristics for various temperatures. (b) Schematic illustration of spin accumulation in spin-injection and spin-extraction conditions. ΔV_{3T} - B_Z curves at (c) $I = -1.0$ and (d) $1.0 \mu\text{A}$ at 40 K, and fitting results with Lorentzian function (solid curves).[13] (e) The magnitude of the observed spin accumulation signals, $|\Delta V_{\text{Hanle}}|$, as a function of bias current I for various temperatures.

To examine these phenomena, first of all, temperature dependences of resistivity (ρ_{Si}) and carrier density (n) were shown in the inset of Fig. 2(a), where ρ_{Si} and n were measured directly by four-terminal transport and Hall effect measurements. Both ρ_{Si} and n have strong temperature dependence in $T < 100$ K, nearly consistent with the feature of a general nondegenerated Si.[22] In this context, we should consider the component of $|\Delta V_{\text{Hanle}}|$ associated with changing ρ_{Si} on the basis of the spin diffusion model.[21] Since the spin-related voltage changes in Si are proportional to $\rho_{\text{Si}} \times \lambda_{\text{Si}}$, [21] the variation in ρ_{Si} with changing temperature can affect $|\Delta V_{\text{Hanle}}|$ in our measurements. The detail is discussed later.

Next, in Fig. 3 we examined $|\Delta V_{\text{Hanle}}|$ versus V_{Int} , i.e., the bias voltage at the CoFe/Si interface for various temperatures. The $|\Delta V_{\text{Hanle}}|$ in $V_{\text{Int}} > 0$ has an evident maximum value at a certain V_{Int} , where $V_{\text{Int}} > 0$ indicates spin-extraction conditions ($I > 0$). This means that there is the most sensitive V_{Int} value for detecting spin-accumulation signals in $I > 0$. We would like

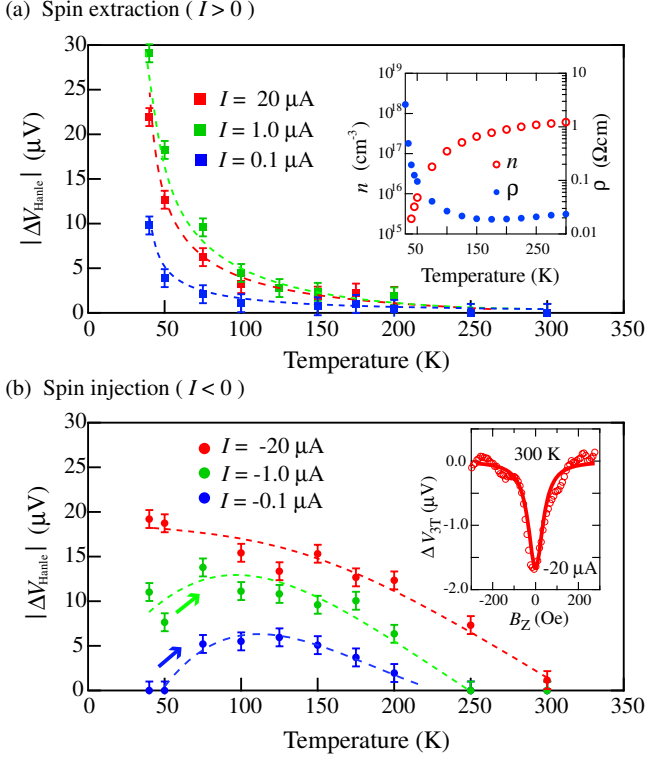


FIG. 2: (Color online) Temperature dependence of $|\Delta V_{\text{Hanle}}|$ for (a) spin-extraction ($I > 0$) and (b) spin-injection ($I < 0$) conditions. The inset of (a) shows carrier density and resistivity as a function of temperature for the Si channel used in this study. The inset of (b) displays room-temperature Hanle-effect signal at $I = -20 \mu\text{A}$ and the fitting curve with Lorentzian function.

to define the detectability for the spin accumulation signals as the sensitivity of the spin detection at the biased contact. In general, the sensitivity of the spin detection at the Schottky-tunnel-barrier contacts has already been discussed for ferromagnet/semiconductor lateral devices.[2, 4, 23–25] The observed feature also implies that we should consider the sensitivity of the spin detection for our CoFe/Si Schottky-tunnel-barrier contacts. However, when we focus on the temperature evolution of $|\Delta V_{\text{Hanle}}|$ at a certain $V_{\text{Int.}}$, the feature of the reduction in $|\Delta V_{\text{Hanle}}|$ with increasing temperature is relatively simple in $V_{\text{Int.}} > 0$. Namely, we do not need to consider the change in the spin-detection sensitivity with temperature evolution in $I > 0$. On the other hand, there is almost no clear correlation between $|\Delta V_{\text{Hanle}}|$ and $V_{\text{Int.}}$ in $V_{\text{Int.}} < 0$, where $V_{\text{Int.}} < 0$ indicates spin-injection conditions ($I < 0$). We find that in $-0.1 \text{ V} \leq V_{\text{Int.}} \leq 0 \text{ V}$ $|\Delta V_{\text{Hanle}}|$ at 75 and 100 K is higher than that at 40 and 50 K. Namely, for $I < 0$, we should also consider the sensitivity of the spin detection with temperature evolution.

Here we also concentrate on the variation in the interface resistance ($R_{\text{Int.}}$). The inset of Fig. 3 shows $R_{\text{Int.}}$ as a function of temperature for various I conditions. Since

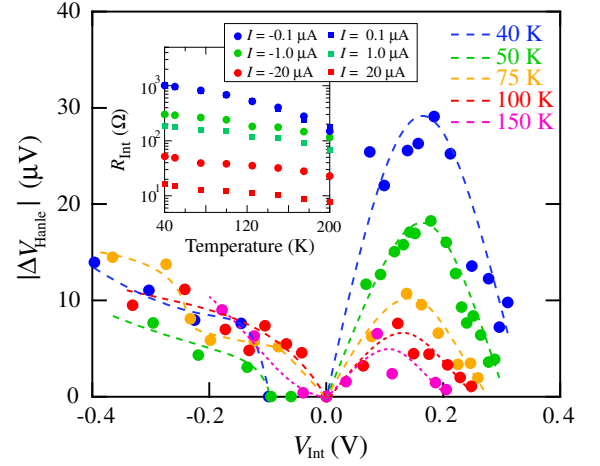


FIG. 3: (Color online) $|\Delta V_{\text{Hanle}}|$ as a function of $V_{\text{Int.}}$ for various temperatures. The insets show temperature-dependent $R_{\text{Int.}}$ for various I conditions.

the $I - V$ characteristics of our device are nonlinear features, the $R_{\text{Int.}}$ values can be varied with changing I . It should be noted that $R_{\text{Int.}}$ slightly decreases with increasing temperature for all I conditions. Hence $V_{\text{Int.}}$ can also slightly be changed by the variation in temperature even if we use the same I condition for the spin injection or extraction.

Considering these features described so far, we discuss the temperature evolution of $|\Delta V_{\text{Hanle}}|$. Under spin-extraction conditions ($I > 0$) [see Fig. 4(a)], we do not have to consider the temperature-dependent sensitivity of the spin detection at a certain $V_{\text{Int.}}$, as described in previous paragraph. We explain the detailed picture as follows. When the electrons tunnel from the Si conduction band into the spin-polarized empty states in CoFe at low temperature (e.g. 40 K) under $V_{\text{Int.}}$ ($\mu_{\text{Int.}}$), the spin accumulation ($\Delta\mu$) can be formed in the Si conduction band, as shown in the left figure of Fig. 4(a). In this situation, the spin-dependent tunneling of electrons is dominant at the Fermi level (see-dashed pink line), leading to the detection of $\Delta\mu$. As the temperature rises [e.g. 100 K, see right figure of Fig. 4(a)], $V_{\text{Int.}}$ is reduced, resulting in a small decrease in $\mu_{\text{Int.}}$. Simultaneously, n is steeply enhanced from $n \sim 10^{15}$ to $\sim 10^{17} \text{ cm}^{-3}$, causing the rapid decrease in ρ_{Si} . As a result, though the $\Delta\mu$ value decreases markedly based on the spin diffusion model,[21] there is almost no difference in the basic situation for the detection of $\Delta\mu$ after the rise of temperature. In other words, we can detect $\Delta\mu$ induced by the spin extraction irrespective of temperature because the spin-dependent tunneling of electrons is maintained. Therefore, there is the sensitivity of the spin detection. In this case, since $\Delta\mu$ in the Si conduction band is related directly to the observed $|\Delta V_{\text{Hanle}}|$ values, the change in ρ_{Si} can dominantly affect the $|\Delta V_{\text{Hanle}}|$ values on the basis of the spin diffusion model. In Fig. 2(a) we can find the steep and gradual decreases in $|\Delta V_{\text{Hanle}}|$ in $T < 100$

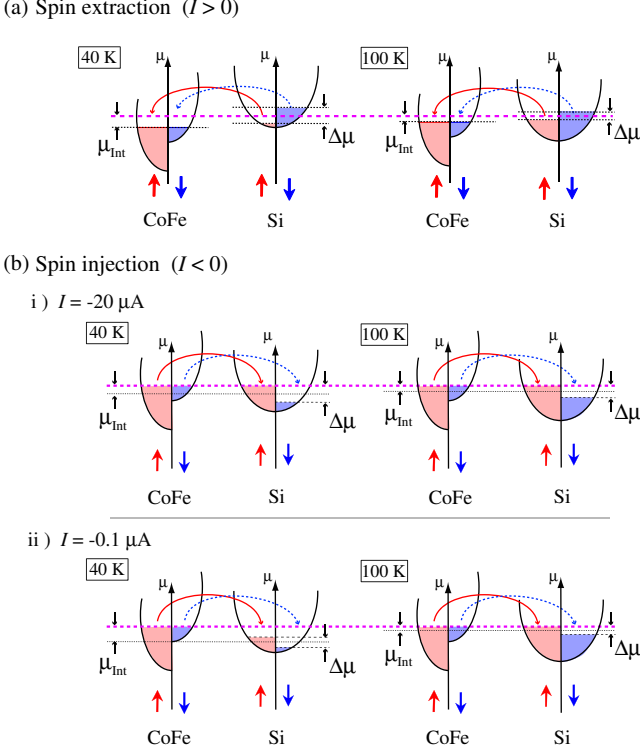


FIG. 4: (Color online) Schematic diagrams of the change in the spin accumulation signals for various temperatures. (a) Spin-extraction conditions at 40 and 100 K and (b) spin-injection conditions at 40 and 100 K with a i) high and ii) low bias current.

K and $T > 100$ K, respectively. Since ρ_{Si} in $T > 100$ K is almost constant, the contribution of ρ_{Si} to the decrease in $|\Delta V_{\text{Hanle}}|$ can be ignored in $T > 100$ K. We infer that, for spin-extraction conditions, the features in $T < 100$ K and $T > 100$ K are dominated by the reduction in ρ_{Si} and λ_{Si} (increase in the spin-flip scattering in Si), respectively. It seems that the change in $|\Delta V_{\text{Hanle}}|$ influenced by the spin-flip scattering is relatively small in the device with a nondegenerated Si channel.

Under spin-injection conditions ($I < 0$), by contrast, we have to consider two different cases whether the injection current is relatively large or not, as shown in Fig. 4(b). When the large injection current (e.g. $I = -20 \mu\text{A}$) is used, the relatively large $\Delta\mu$ can be demonstrated.[19] Thus $\Delta\mu$ induced in the Si conduction band can reach the Fermi level of the spin-polarized tunneling electrons at any temperatures. When the temperature rises, $\Delta\mu$ is merely reduced (middle figures) by the same mechanism of Fig. 4(a). Namely, we can still obtain the sensitivity of the spin detection. On the other hand, if the injection current is relatively low (e.g. $I = -0.1 \mu\text{A}$) at 40 K, $\Delta\mu$ induced in the Si conduction band is quite small. Since the relatively large μ_{Int} is applied in the low bias current regime at 40 K, we can understand that the position of the quasi Fermi level of the spin-polarized electrons in the Si conduction band is quite lower than the Fermi

level (dashed pink line) of the spin-polarized tunneling electrons from CoFe. In this situation, the spin-polarized electrons can tunnel into the unpolarized states (unoccupied states) in the Si conduction band. Thus we could not obtain $\Delta\mu$ as a consequence of the $|\Delta V_{\text{Hanle}}|$ measurement at $I = -0.1 \mu\text{A}$ and 40 K. This means that there is no sensitivity of the spin detection. The similar situations have already been reported for Fe/GaAs devices previously,[2] and we have also reported the above features in detail for the CoFe/Si devices.[19]

Why we can see that $|\Delta V_{\text{Hanle}}|$ appears at 100 K for $I = -0.1 \mu\text{A}$ despite the rise of temperature? Shown in the right figure of the bottom in Fig. 4(b) is a possible schematic illustration of the interpretation of the spin detection. As previously described, when the temperature rises up to 100 K, n is enhanced from $n \sim 10^{15}$ to 10^{17} cm^{-3} , causing the rapid decrease in ρ_{Si} . As a result, $\Delta\mu$ is also reduced on the basis of the spin diffusion model.[21] Simultaneously, since V_{Int} also decreases with decreasing R_{Int} , the reduction in μ_{Int} also occurs. Accordingly, the Fermi level of the spin-polarized tunneling electrons is located on $\Delta\mu$ induced in the Si conduction band, leading to the appearance of the sensitivity of the spin detection. This can be considered to be the same situation for $I = -20 \mu\text{A}$ at 40 K shown in the left figure of Fig. 4(b). This is a possible mechanism of the appearance of the spin accumulation signals ($|\Delta V_{\text{Hanle}}|$) with increasing temperature, observed in Fig. 2(b). Such qualitative consideration has already been explained in terms of the change in the spin-detection sensitivity at the tunnel contact.[2, 23–25] We emphasize that the tuning of V_{Int} (μ_{Int}) is a key to detect $\Delta\mu$ induced by the spin injection.

We finally comment on the difference in the actual temperature evolution of the decrease in $|\Delta V_{\text{Hanle}}|$ between spin-extraction ($I > 0$) and spin-injection ($I < 0$) conditions for the large currents of $I = \pm 20 \mu\text{A}$ [see Figs. 2(a) and (b)]. As mentioned above, the temperature dependent $|\Delta V_{\text{Hanle}}|$ for $I > 0$ can be explained mainly by the change in ρ_{Si} . On the other hand, for $I < 0$, we should consider not only the contribution of ρ_{Si} and λ_{Si} to $|\Delta V_{\text{Hanle}}|$ but also that of the spin-detection sensitivity to $|\Delta V_{\text{Hanle}}|$. Though $|\Delta V_{\text{Hanle}}|$ is reduced with decrease in ρ_{Si} and λ_{Si} , the sensitivity of the spin detection is enhanced in a low current bias regime at the same time. This opposite feature causes the relatively gradual decrease in $|\Delta V_{\text{Hanle}}|$ at $I = -20 \mu\text{A}$ compared with that at $I = +20 \mu\text{A}$, as shown in Fig. 2. In our opinion, it is very important for room-temperature device operation[15] to understand the temperature-dependent sensitivity of the spin detection at the Schottky-tunnel-barrier contact in devices with a nondegenerated Si channel.

IV. CONCLUSION

We have studied temperature evolution of spin accumulation signals obtained by the three-terminal Hanle

effect measurements for the device with a nondegenerated Si channel. The clear difference in the temperature-dependent spin signals between spin-extraction and spin-injection conditions was seen. We found that it is important for the consideration of the temperature evolution to understand not only the mechanism based on the spin diffusion model but also the sensitivity of the spin detection at the Schottky-tunnel-barrier contact. These results are also important to enhance the spin signals in the device applications at room temperature.

Acknowledgments

This work was partly supported by PRESTO-JST and STARC. Three of the authors (Y.A. K.K. and S.Y.) acknowledge JSPS Research Fellowships for Young Scientists.

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